1. LEVEL II

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22p.

THE CHARACTERISTICS OF THE CUTANEOUS COMMUNICATIONS CHANNEL [1]

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We will discuss the specialized characteristics of a communications channel which uses the peripheral nerves of the skin as port of entry for intelligence directed to a human receiver. The first slide (Fig. II) shows the general form which any communications channel must take when it is desired to transmit a message from one human to another. In particular we are concerned with the last two boxes on this slide, but as in any interconnected system the characteristics of all the parts interplay one with the other. Thus, the form of the transmission from the human originator on the extreme left side of the slide, and the noise and error contributions of the black boxes immediately following are all significant. Also pertinent to our problem are:

(1) the noise and other signal distortion properties of the distributed link which connects the transmitting location with the receiving location, and

(2) the "black box" receiving system which prepares the now-noise-corrupted signal for transmission across the man-machine interface.

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Of course, all truly useful communications systems should be bilateral and thus, in principle, we should be able to by-pass the conventional acoustic transmitter of the human originator just as is depicted conceptually in the next slide, "Picking up Biological Signals". Some non-penetrating electrodes have been designed (Dr. Ross Adey of UCLA, and others), which show promise in this direction. But this phase of the total channel is beyond the scope of this paper. We are concerned with the afferent signals proceeding from the skin along the basic communications link, The Neuron, slide 3, to the human brain.

The series of experiments we are describing today are aimed at improving the effective signal to noise ratio of the afferent signal by two means. The first means consists of sending a cueing signal over the cutaneous neuronal pathways to the brain, in conjunction with a noise-corrupted audio signal over the auditory neuronal pathways to the brain. A white noise signal was linearly added to the audio signal and the combination was passed through a 300 Hz to 3000 Hz filter before the signal-to-noise ratio was measured. In this case we are relying upon the ability of the central nervous system to perform various non-linear signal analysis and synthesis operations, so as to extract a higher signal to noise ratio than that of the acoustic signal alone. Our results indicate a statistically significant margin of signal to noise enhancement may be obtained by this means.

Our second experiment, also using two neuronal pathways, employed a diversity reception scheme where the primary signal as well as the secondary or "shadow" signal are both received in the cutaneous modality. The shadow signal is appropriately delayed to permit a combining of signal effects which tend to sharpen the acuity of sensation within the peripheral nervous system with respect to bandwidth or speed of reception of intelligence.

Thus, in a simple overview, our signal to noise enhancement experiment attempted to enhance primarily the acuity of the central nervous system, while our diversity reception scheme attempted to enhance primarily the acuity of the peripheral nervous system. As we mentioned previously however, all elements in a general communications channel interact with all the others, and therefore, experiments aimed primarily at increasing the efficiency of the peripheral receptors, of necessity also affect the central nervous system and vice versa.

METHOD

Subjects

All subjects utilized in the experiments herein reported were soldiers from the US Army Signal Center and School. Asked to volunteer at an interval of training which would avoid any disruption of schedules, they were not paid for their services. They were medically screened for cardiac, dermatological and emotional normality. As a rule, they were utilized on two successive days, except when a weekend or holiday intervened. Data collection proceeded at once, after a brief

orientation on the first day, for all experiments except Acuity Experiment I. For that experiment, the first day was a day of familiarization and training, and the second day served for data collection.

Table I lists the population numbers, the mean ages and age ranges of the soldiers utilized in the two Acuity and the two Signal/Noise Ratio Enhancement Experiments.

TABLE I

NUMBERS AND AGES OF SOLDIERS UTILIZED
IN THE
ACUITY AND S/N RATION ENHANCEMENT EXPERIMENTS

EXPERIMENT	NUMBER OF SOLDIERS	AGE RANGE	MEAN AGE
Acuity I	11	18-37	23
Acuity II	8		
S/N Ratio I	8	19-23	20
S/N Ratio II	8	19-25	21

Equipment

Acuity Experiments

Figure I, "Acuity Experiments Stimulus Apparatus", shows the apparatus employed in Experiment I. The Primary Signal Generator was a Rutherford Pulse Generator, Model B7B. The Shadow Signal Generator was a Rutherford Model B-2A. Both the Primary and the Shadow Transducer Constant Current Stimulators were ELS Models CCS-1A. The message programmer, a tape recorder, utilized a pre-prepared two channel audio tape. One channel keyed the constant current

stimulators and caused them to emit 300p.p.s., $\frac{1}{4}$ MSEC. monophasic pulses, $7\frac{1}{2}$ percent duty cycle. Simultaneously, the other channel caused the switching of the proper transducers into the stimulator circuits in a regular sequence. The physical location of these transducers will be shown in a later slide.

First a group of digits would be presented at the primary transducer site alone. Then, the digits would be presented at both the primary transducer site and at one of the three shadow transducer sites. The shadow transducer received the same signal as the primary transducer, but with a time delay of zero, five, or ten milliseconds. The groups of digits were prepared with mechanical keyer on one channel of the audio tape. Control signals, to advance a stepping or sequencing switch, were on the second channel. The stimulus or message signals consisted of bursts of one, two, three, four, five, or six "dots" representing the first six digits respectively, randomly assembled to comprise an experimental session containing 60 or 120 discrete digits. They were presented to the transducers on the arm of the subjects, each digit at an interval of approximately five (5) seconds. Several tapes were prepared which enabled approximation of the equivalent Morse Code rates of 5, 7, 12, 14 and 20 words per minute. Although the Morse Code equivalent rates progressed from the rather slow rate of 5 wpm to the quite fast rate of 20 wpm, the time interval between the groups of "dots", or the digits, remained nominally fixed at 5 seconds. All of our subjects were

allowed to select the level of current he considered acceptable to him. The current usually ranged between 0.1 and 0.9 milliamperes. The subject had a safety cutout switch available to him at all times. A single equivalent Morse Code rate was maintained during any one session. This allowed reception of 10 digits at the primary site, followed by both primary and shadow site reception of 10 digits in regular sequence to utilize the three shadow sites.

Figure II, "Acuity Experiment Response Apparatus", shows the method utilized by each subject to record his message receptions at the higher Morse Code equivalent rates. The telegraph key and the associated Visicorder were employed only at the 20 wpm rate. The subject was asked to repeat on the telegraph key the exact digit he received through the electrocutaneous transducer (ECT). His usual response apparatus, for the rates lower than 20 wpm, was a pad and pencil with which he transcribed the digits as he received them. Error counts were in two categories:

(1) failure of precise recognition, for example, not calling a "6" a 6; and

(2) missing precise recognition by a difference greater than one, for example, calling a "4" either 6, 2 or 1.

Figure III, "S/N Enhancement Apparatus", shows the method used to present acoustic inputs to each subject accompanied by electrocutaneous signals. The Fairbanks Rhyme Test, a test of phonemic differentiation, containing 250 monosyllabic words, was presented simultaneously to four soldiers.[2] Two of the soldiers received acoustic and electroncutaneous

[2]The Fairbanks Rhyme Test is presented in some detail at this Conference in a paper by J.W. Preusse, "Semi-automatic Speech Intelligibility Measurements" (paper TA26.3)

inputs, while two received acoustic inputs alone. After repeating the Rhyme Test a number of times, the soldiers alternated taking the BCT signals. The BCT signal was always presented 260 milliseconds ahead of each stimulus word of the Rhyme Test. For the S/N Ratio Experiment I, the Rhyme Test was administered 10 times. For the S/N Ratio Experiment II, the Rhyme Test was administered 20 times. Figure III shows the type signal, namely biphasic, pulse repetition rate of 300 p.p.s., duty cycle 15-percent, presented by the BME Constant Current Stimulators. The BCT signal lasted for one-tenth of a second and was presented via pin type electrodes to the ventral forearm of the subject's non-writing hand.

Figure V, "Sites of Transducers" shows the locations of attachment of the transducer assemblies on the non-writing arm of the subject in the Acuity Experiment I. Figure VI, "Acuity Experiment II Stimulus Apparatus", shows the apparatus employed in Acuity Experiment II. A biphasic pulse, 300 p.p.s., duty cycle 15-percent, was presented to the subject with a more convenient transducer housing arrangement. Only one Velcro strap was used and the time of application of the energy at each of the four sites was approximately equal. This was accomplished by introduction of an electrode utilization switching network. The time delay network was built into the triggering circuit of the Shadow BME Stimulator. Eight different time delays, namely 0, 2½, 5, 7½, 10, 15, 20, and 28 milliseconds, were introduced in the activation of Primary and Shadow transducers.

Figure VII, "Acuity Experiment II Response Apparatus", is similar to the Response Apparatus for the earlier Acuity Experiment (Figure II), in that it shows the apparatus utilized at the 20 wpm rate. Each subject utilized the pad and pencil format for the lower rates. An important difference was that in Acuity Experiment II each message sheet of 120 digits was divided into two parts. The first 60 digits, assembled in six rows of ten digits, constituted a training session for each subject. The actual ECT digits were printed on each sheet. The subject thus was told visually what the ECT digit was, prior to his reception of each. The second 60 digits were not printed on each sheet. Rather, each subject was required to transcribe this second group of 60 digits. This constituted the data collection part of Acuity Experiment II, and proceeded after a very brief training session. Figure VII shows that both Primary and Shadow transducer input signals, message programmer signals, and the telegraph keyed response signals of the subject were recorded.

Figure VIII, "Typical Application of ECT Assembly", shows that both ventral and dorsal sides were utilized, along the same transverse plane of the subject's non-writing arm. Utilization of four pairs of electrodes, three on the ventral side, and one on the dorsal side, facilitated exploration of the discriminatory value of closely-spaced and more distantly-spaced neuronal pathways.

RESULTS

Acuity Experiment I

Results of Acuity Experiment I, concerned with sharpening of sensation in the peripheral nervous system, are shown in Figure IX.

Figure IX shows that a time delay in the vicinity of 5 milliseconds provided the optimum improvement of accuracy. Figure IXA shows that "Error Free" reception, that is, precise reproduction of the messages was enhanced at a time delay of 5 milliseconds at all Morse Code equivalent rates, except the highest, namely 20 wpm. Figure IXB, "Errors Up To One Unit", shows a generally consistent relationship with respect to percent accuracy of reception, in the relative order of the several Morse Code equivalent rates. Only two of the five Morse Code rates continue to peak at 5 milliseconds. Analysis of the data of Figure IXB suggested that a training period at each Morse Code equivalent rate might help the subjects in the time discrimination problem associated with the various rates.

The sites of the Primary and Shadow transducers, relevant to error-free reception and total errors, at the five Morse Code equivalent rates and at three time delays, are compared in Table II. Inspection of Table II, "Percentages of Error-Free Reception by Eight Subjects at Primary Site Alone and at Combined Primary and Shadow Transducer Sites", shows that the highest percentages of error-free reception were at rates of 5 and 7 wpm. Primary and Shadow sites 1, 2, and 3 include percentages of 90 and higher. Means of the percentages suggest that the optimum of the transducer sites, across all Morse Code equivalent rates, is Primary and Shadow 1. A sharp drop in accuracy between the group containing 5 and 7 wpm on the one hand, and the group containing the 12, 14, and 20 wpm group on the other hand, is clearly indicated in Table II.

TABLE II

PERCENTAGES OF ERROR-FREE RECEPTION OF MESSAGES BY EIGHT SUBJECTS AT PRIMARY SITE ALONE AND AT COMBINED PRIMARY AND SHADOW TRANSDUCER SITES

SITE	TIME DELAY (Msec)	MORSE CODE EQUIVALENT RATES (wpm) 5	7	12	14	20
Primary Alone		71	70	32	35	41
		83	70	34	31	32
		83	75	39	25	41
Primary and Shadow 1	0	87	78	41	40	38
	5	93	80	42	47	37
	10	94	76	37	45	20
Primary and Shadow 2	0	78	82	41	30	45
	5	92	80	43	23	18
	10	90	74	37	22	35
Primary and Shadow 3	0	75	62	40	25	35
	5	92	67	28	28	30
	10	91	54	30	28	25

NOTE: Percentages are based on a total of 6335 "Message" Attempts.

Acuity Experiment II

Preliminary results of Acuity Experiment II (at time of this writing, data of only four subjects are available), are summarized in Table III, "Percentages Achieved by First Four Subjects of Acuity Experiment II in Receipt of Electrocutaneous Messages with Compound Transducers", and in Figure X, "Summary of First Four Subjects of Acuity Experiment II."

TABLE III

PERCENTAGES ACHIEVED BY FIRST FOUR SUBJECTS OF ACUITY EXPERIMENT II IN RECEIPT OF ELECTROCUTANEOUS MESSAGES WITH COMPOUND TRANSDUCERS

TIME DELAY (Msec)	PERCENTAGES AT THE MORSE CODE EQUIVALENT RATES (wpm)				
	5	7	12	14	20
0	84	70	41	47	30
2.5	88	72	60	69	39
5	20	45	42	28	25
7.5	86	56	41	42	38
10	76	61	44	38	42
15	90	60	49	42	56
20	75	64	58	50	51
28	38	46	20	32	28

Inspection of Table III shows a peaking of achieved accuracies for three of the five Morse Code equivalent rates at 2½ Msec. The exception is at the 20 wpm rate, which peaks at the 15 Msec delay. The 5 wpm data shows a second peak also at 15 Msec. All four subjects provided data for time delay of zero. Two subjects each provided data for time delays of 2½, 7½, 10, 15, and 20 Msec. Only one subject each provided data for time delays of 5 and 28 Msec.

S/N Ratio Enhancement Experiment I

The results of S/N Ratio Enhancement Experiment I are shown in Figure XI, "Percent Intelligibility Achieved by Eight Soldiers Over Ten Replications of the Fairbanks Rhyme Test, With and Without ECT Signal", and in Table IV, "Improvements in S/N Ratio for Eight Subjects at 0db and -5db Attributable to Electrocutaneous Cueing". Figure XI shows the improvement in the overall average of results of the Fairbanks Rhyme Test, a matter of significance primarily in connectors with studies of the validity of the Fairbanks Rhyme Test itself. For purposes of our investigation, the significant figures are those which indicate the improvement of the accuracy of each individual when electrocutaneous cueing is utilized. The average of these individual improvements, summarized in Table IV, are in terms of the effective improvement of S/N Ratio. This means that, if the S/N Ratio had been improved by this amount, the individual's performance without ECT would have been equivalent to his achievement with ECT on the more degraded signal.

Table IV shows that at 0 db, the Effective Improvement is .4 db, while at -5 db, the Effective Improvement is 3.1 db. The next two lines, "Improvement Component", and "Degradation Component" indicate the composition of the "Effective Improvement".

TABLE IV

IMPROVEMENTS IN S/N RATIO FOR EIGHT SUBJECTS AT 0 DB AND -5 DB ATTRIBUTABLE TO ELECTROCUTANEOUS CUEING

	Improvements			
	0 Db		-5 Db	
Effective Improvement	.4 db	(70)*	3.1 db	(75)
Improvement Component	3.1 db	(52)	6.7 db	(51)
Degradation Component	-7.2 db	(18)	-4.4 db	(24)

*Figures in parentheses represent the number of repetitions of the Fairbank Rhyme Test (250 phonemes)

S/N Ratio Enhancement Experiment II

The results of S/N Ratio Enhancement Experiment II are contained in Figure XII. There are no significant differences between time delays of 130, 260, and 390 Msec, when all data are treated together. However, an inspection of the percentages achieved by individuals showed, fairly consistently, improved performance with a time delay of 260 Msec.

DISCUSSION OF RESULTS AND CONCLUSIONS

Perception of the electrocutaneous stimulus is slow. It may be associated with the sensation of diffuseness of the electrical stimulus. The electrical and the neurological nature of the problem can be understood in terms of the cutaneous impedance model (Bennett et al., 1966), which hypothesized three principal levels of resistance in the skin. ECOM experiments have demonstrated the electronic, ionic and electrode surface complexity of the cutaneous impedance. Quotidien stability and p.16 diurnal variability of finger resistance have been reported by Sheridan et al (1966). Bekesy reports that "Both summation and inhibition vary with the amplitude of the vibration, the distance between the stimulated areas, the slope of the spatial distribution of the stimulus along the surface of the skin, its time pattern and the density of the innervation." (*Experiments in Hearing*, p. 610). Bekesy (*Ibid.*, p. 571) also reported the work of Katz, who demonstrated that the phenomenon of directional hearing can be duplicated on the skin. Bekesy reports as follows: "For a closer investigation of this phenomenon, two tips attached to two electromagnetic driving units were placed on both sides of the end of the thumb, or on two points about 12 cm apart on the inner side of the arm. A timing device was used to discharge two condensers through the driving units with a certain time delay . . . When the vibrator on the left . . . received its current earlier than the driver on the right side, for large time differences two discrete, sharp pulses were felt on the skin, one on the left side followed by one on the right. The intensity of the two pulses

was about the same . . . As the time delay was made smaller, however, the sensory intensity on the right side decreased . . . whereas the intensity on the left side increased until the effect on the right side was completely suppressed and the whole thrust produced by the pulses was felt only on the left side . . . As the time delay approached zero, the area of the sensation moved to a position halfway between the two tips, its size increased, and its intensity decreased."

It appears feasible and desirable to do with biphasic electrical pulses what Katz did with mechanical vibrators and to proceed with the possibilities afforded by our instrumentation to improve the acuity problem. Thus electrocutaneous communications possibilities at higher orders of speed are opened up. Our results in Acuity Experiments I and II show that time delay does indeed increase acuity. The time delay which is optimum, however, was found to be a very sensitive function of degree of training of the operator, his state of mind and physical condition (i.e. boredom, fatigue, and motivation). Another factor which must be taken into account is the ratio of the time delay to the spacing between the individual dots of a digit or message. As this ratio starts to exceed one tenth, accuracy of reception begins to drop. When all these factors are taken into account, the most likely region for the location of an optimum delay time appears to be between two and five milliseconds. Secondary optima appear to exist between ten and twenty milliseconds but this latter group will probably be restricted (by the aforementioned 0.1 ratio boundary) to cyclic rates not higher than about 7 wpm.

Now let us consider the results obtained in the Signal to Noise Enhancement Experiments I and II. These results indicate that the use of electrocutaneous cueing signals effectively enhance the noise degraded incoming signal by about 3 db for incoming S/N ratios of the order of -5 db. The effective S/N enhancement diminishes as the incoming S/N ratio improves. However, the need for electrocutaneous cueing in this region also diminishes. Thus, precisely when it is most needed, the electrocutaneous cueing technique appears to be most effective. The degree of time difference between the audio message and the cueing signal was found to vary with the degree of fatigue or boredom of the operator. If the cueing signal preceded the acoustic signal by 260 milliseconds optimum results were secured when the operators were relatively fresh and wide-awake. As they became more tired or bored the optimum value appeared to shift to a value between 260 milliseconds and 390 milliseconds. More investigation is required to fix the location of the optimum time with which the cueing signal should precede the acoustic signal as a function of the degree of operator fatigue.

As an overall conclusion, it can be said that the investigation to date indicates that the sharpening of acuity of reception of electrocutaneous messages can be achieved by the use of "shadow" signals delayed in time and displaced in location from the primary signal. The ventral-dorsal combination on the forearm offers particular promise. Similarly the use of an electrocutaneous signal as a secondary cueing channel in conjunction with a primary acoustic channel has been shown to result in an effective 3 db signal to noise enhancement of the acoustic channel when that channel is degraded to the level of -5 db.

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ACUITY EXPERIMENT STIMULUS APPARATUS

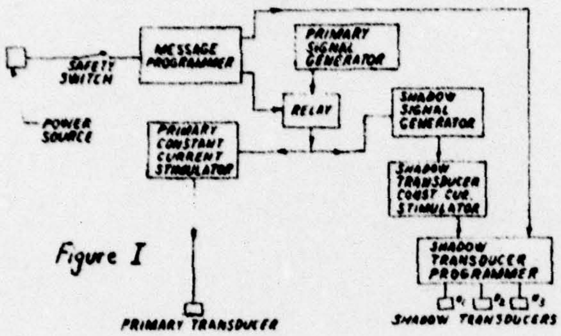


Figure I

ACUITY EXPERIMENT RESPONSE APPARATUS

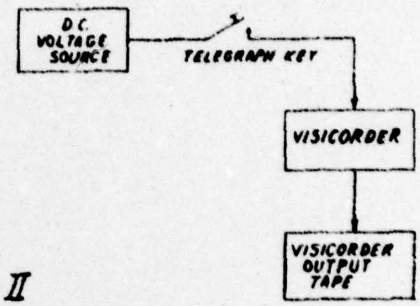


Figure II

S/N ENHANCEMENT EXPERIMENT APPARATUS

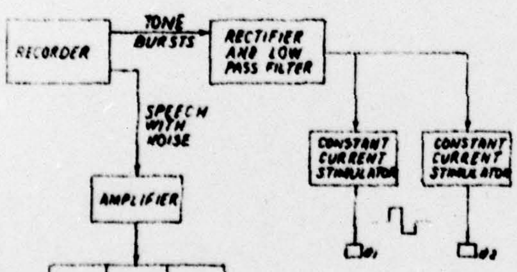


Figure III

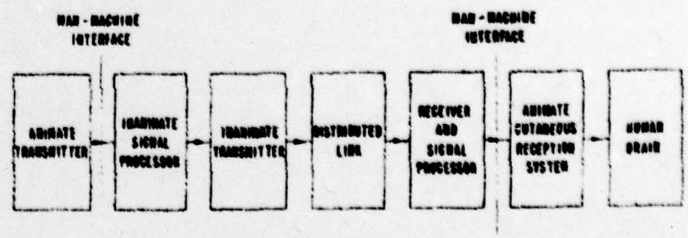


FIG IV GENERALIZED COMMUNICATIONS CHANNEL

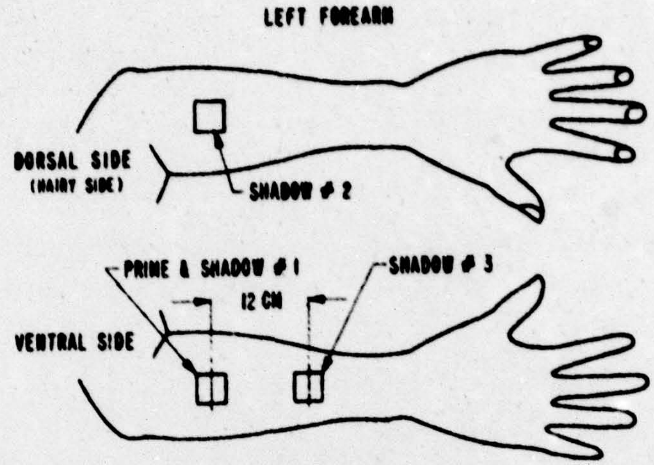


FIG. V CUTANEOUS TRANSDUCER SITES

ACUITY EXPERIMENT II STIMULUS APPARATUS

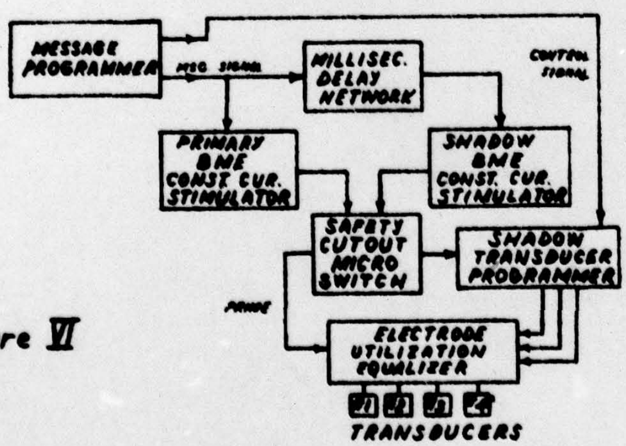


Figure VI

ACUITY EXPERIMENT II RESPONSE APPARATU.

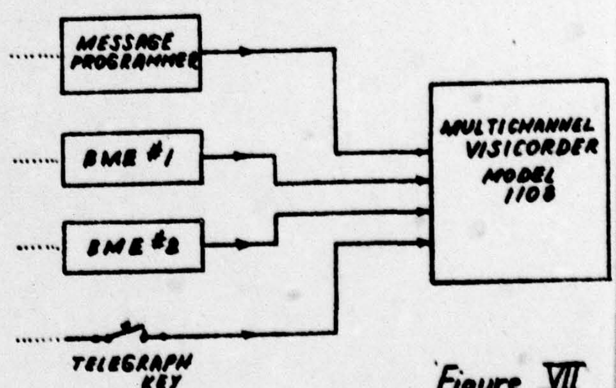
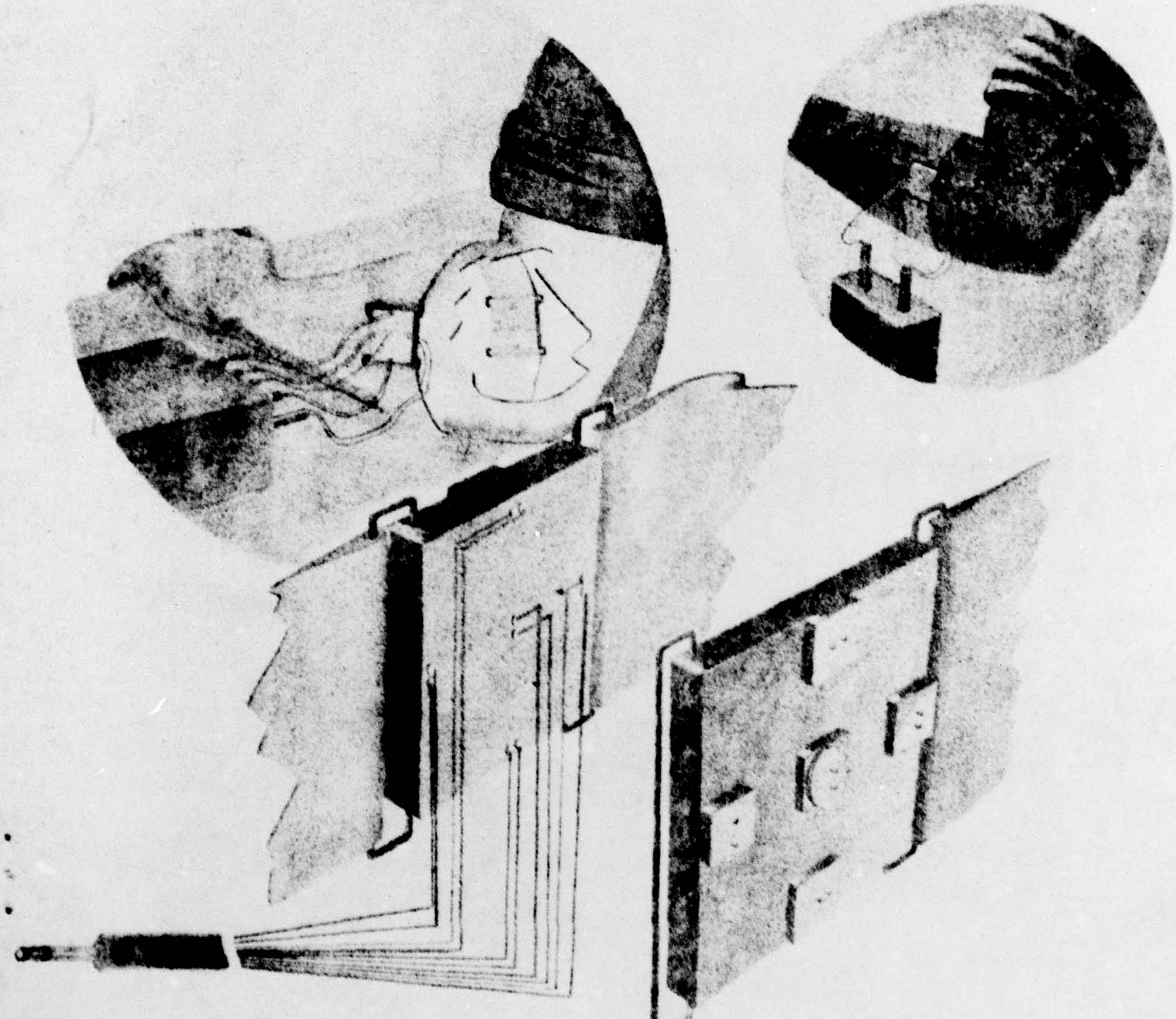


Figure VII

FIG. VIII TYPICAL APPLICATION OF ECT ASSEMBLY



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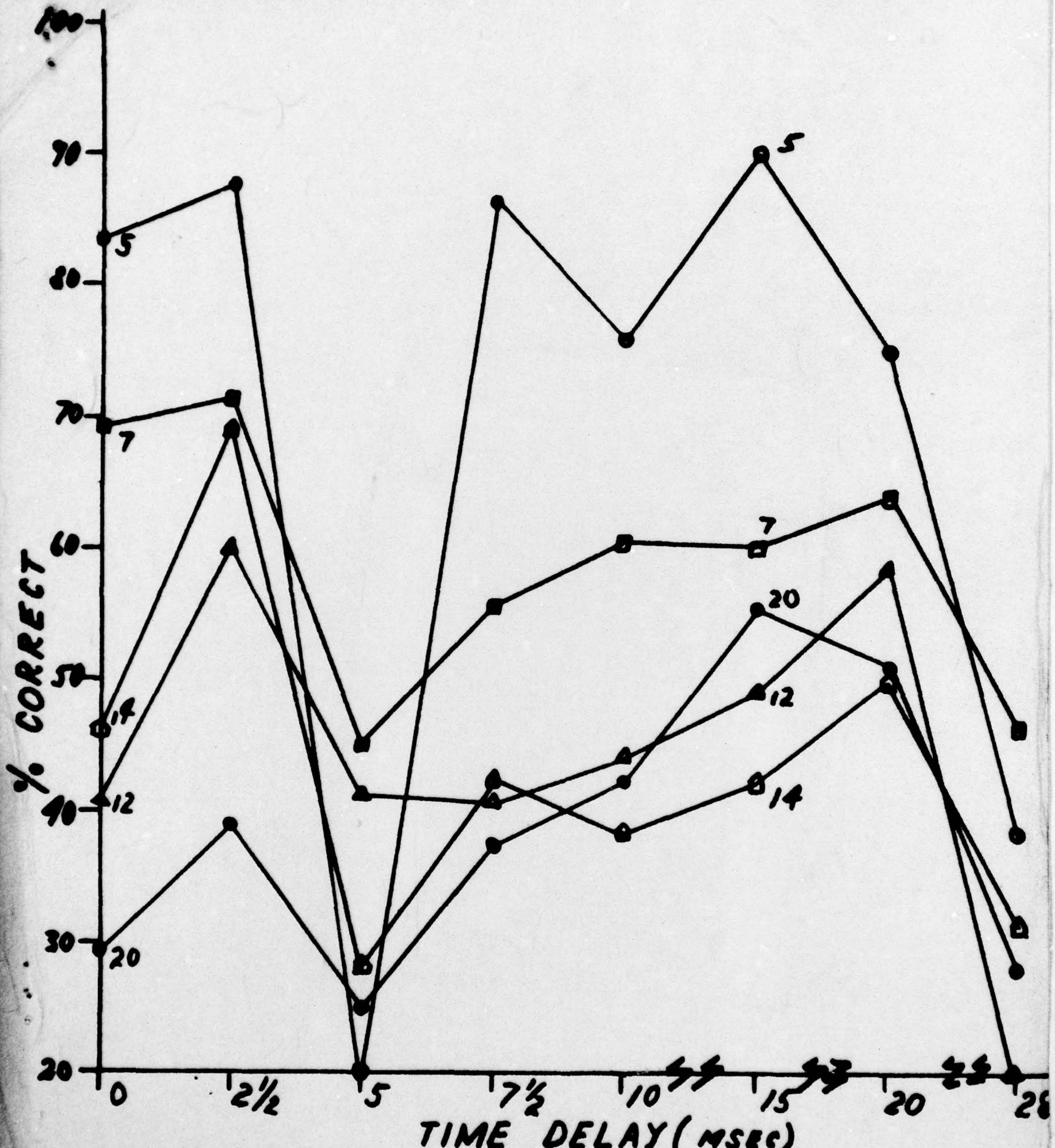

Fig. X SUMMARY OF FIRST FOUR SUBJECTS OF ACUITY EXP. II.

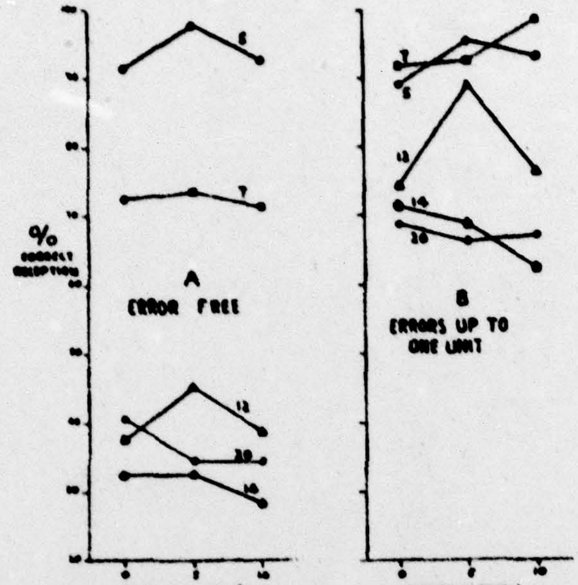

FIG. 10 PERCENT CORRECT SCT RECEPTION BY ELEVEN SOLDIERS AT MORSE CODE EQUIVALENT RATES OF 5, 7, 13, 14, AND 20 WPM., WITH THREE TIME DELAYS

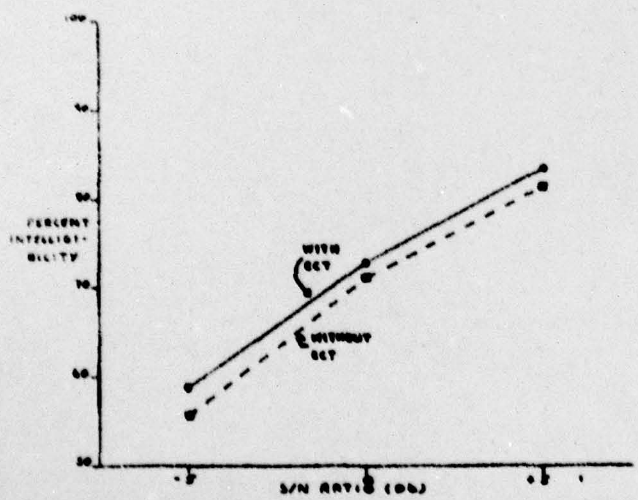

FIG. XI PERCENT INTELLIGIBILITY ACHIEVED BY EIGHT SOLDIERS OVER TEN REPLICATIONS OF THE FAIRBANKS RHYME TEST, WITH AND WITHOUT SCT SIGNAL

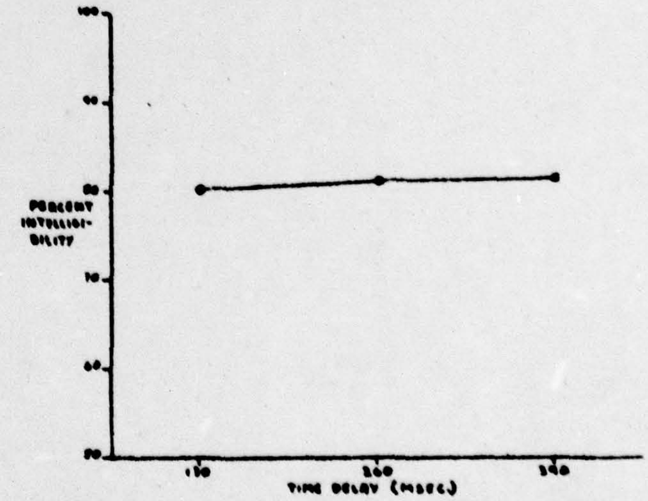

FIG. XII PERCENT INTELLIGIBILITY ACHIEVED BY EIGHT SOLDIERS OVER TWENTY REPLICATIONS OF THE FAIRBANKS RHYME TEST AT +5DB S/N RATIO, WITH THREE DELAYS OF THE SCT SIGNAL